Marine Policy 62 (2015) 326–336

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Multifactor productivity, environmental change, and regulatory impacts in the U.S. West Coast groundfish trawl fishery, 1994–2013

Aaron Mamula [a,*], Trevor Collier [b]

[a] Fisheries Ecology Division, Southwest Fisheries Science Center National Marine Fisheries Service National Oceanic and Atmospheric Administration, 110 Shaffer Road, Santa Cruz, CA 95060, USA
[b] Department of Economics and Finance, University of Dayton, Dayton, OH, USA

A R T I C L E I N F O

Article history:
Received 1 June 2015
Accepted 1 June 2015
Available online 27 June 2015

Keywords:
Lowe Index
Productivity
Groundfish
Catch shares

A B S T R A C T

This paper provides estimates of multifactor productivity for vessels participating in the West Coast Limited Entry groundfish trawl fishery from 1994 to 2013. Impacts of regulatory change on productivity are examined and productivity dynamics are evaluated across spatial and behavioral dimensions. Results suggest four different periods of consistency: (i) a decline in productivity from 1994 to 2002, (ii) a sharp increase in productivity following a permit buyback in 2003, (iii) stagnant productivity from 2005 to 2010, and (iv) another increase in productivity following implementation of individual transferable quotas ("catch shares"). Important spatial differences in productivity are uncovered-vessels fishing south of 40°10′ N latitude were generally less productive than those fishing north of the same line. Additionally, the productivity gap between north and south was enlarged following the policy changes (buyback in 2003 and catch shares in 2011). Productivity from 1994 to 2013 tended to be higher among vessels that were more diversified in terms of their total portfolio of commercial fishing revenue. However, productivity tended to be lower among vessels whose targeting strategies were more diversified within the groundfish fishery.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Productivity has served as an important metric for evaluating the performance of commercial fishing vessels and fishing fleets both within the United States and internationally (See [1-3] for examples from fisheries around the world). Often, productivity emerges as the best feasible measure of firm or fleet performance since high resolution micro data that might permit direct evaluation of profitability is rare in regulated fisheries. Even when direct evaluation of firm profits is possible, productivity remains a valuable metric as it can be used to help fisheries managers understand the drivers of profitability change.

This paper estimates productivity change at the vessel level for firms participating in the so-called non-whiting, shoreside sector of the Limited Entry West Coast Groundfish Trawl Fishery (hereafter referred to as groundfish trawl) from 1994 to 2013. The fishery has experienced many regulatory changes during this time including implementation of a license limitation program in 1994, a permit buyback in 2003, which was conducted in concert with the introduction of a system of coast wide spatial closures, and the implementation in 2011 of catch share management. Under catch shares, total allowable catch (pounds) of each managed species was allocated to individual vessels and these allotments were transferable. The primary purpose of this paper is to examine the impact of regulatory changes on productivity for vessels belonging to different subgroups within the groundfish trawl fleet.

As noted in [4], fisheries managers are generally concerned not only with the overall costs and benefits of regulatory intervention but also with how benefits and costs are distributed among vessels or groups of vessels within a fishing fleet. They specifically identify (i) sustained participation of small owner operated vessels, (ii) avoiding geographic consolidation of fishing activity, and (iii) encouraging diversity of the fishing fleet as important goals for fisheries managers. This study addresses these management concerns by providing estimates of an important metric of fishing success for each vessel in the fleet.

In this study productivity dynamics are compared for the following management relevant vessel groupings:

- Spatial: The West Coast commercial groundfish trawl fishery extends from about 34°27′ N latitude in the south to the US-Canadian border in the north, covering almost the entire West Coast of the US. Productivity growth is compared over

* Corresponding author.
E-mail address: Aaron.Mamula@NOAA.GOV (A. Mamula).

http://dx.doi.org/10.1016/j.marpol.2015.06.002
0308-597X/© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Fig. 1. International North Pacific Fisheries Commission area boundaries for the US West Coast.

multiple management regimes for vessels participating in different regions of this fishery.

- Behavioral: Vessels participating in this fishery differ from one another along a number of observable behavioral dimensions including the amount of annual fishing time allocated to the groundfish fishery relative to other fisheries, such as crab, shrimp, and various hook and line fisheries. Additionally, groundfish trawl vessels harvest over 60 distinct species of fish. Some vessels can be distinguished by their preferences for targeting certain species within this multispecies fishery. Observable behaviors such as species targeting patterns and fishery participation levels are examined for correlation with productivity differences.

The primary metric for measuring productivity in this study is the Lowe Multifactor Productivity Index [5]. Although vessel groupings were created mainly to establish consistency with groups of potential interest to fisheries managers on the US West Coast, similar groupings have been used to form vessel comparisons by [6] (fleet segmentation based on participation levels) and [3,7] (fleet segmentation based on geography).

The remainder of the paper adheres to the following structure. Section 2 describes the study area, including some detail on the history of biologic and regulatory changes in the fishery. Section 3 details the methods used in this study. Section 4 presents the data and Section 5 presents results and discussion. The final section offers a summary of key results and recommendations for future work in this area.

2. Study area and background

Fig. 1 illustrates the spatial extent of the fishery which extends from waters off the coast of Santa Barbara, California in the south to the U.S.–Canada border in the north. The remainder of this section provides a condensed background of the regulatory history of the groundfish trawl fishery. A number of resources are available for readers interested in a deeper background. They include [8–11] (economic development, regulatory history, and spatial development of the fishery); [12,13] (species abundance, spatial distributions and environmental influences); [14,15] (changes in spatial distribution of fishing effort and landings in response to policy change)

The "Groundfish Fishery" refers to a variety of flatfishes (such as Dover sole and petrale sole), roundfishes (such as sablefish and lingcod) and rockfishes that live on or near the ocean floor and are often harvested together. Appendix A details the species included in this study. This study focuses on groundfish trawlers. These are vessels which harvest the many species of groundfish using bottom trawl gear, generally a large net that is towed along the ocean floor.

An interesting feature of the West Coast groundfish fishery is that different species of groundfish prefer different habitat types. This means that, although fishermen cannot exercise perfect control over which species they harvest, they can take some measures (such as fishing in different locations or with different types of nets) that will tend to produce predictable mixes of species.

A second interesting feature of this fishery is that different species have different growth rates and therefore have different levels of sensitivity to fishing pressure. The fishery is managed according to regulations, which are set with the goal of avoiding excessive harvest of species whose populations are depleted, while maintaining opportunities for fishermen to harvest healthier populations. This management goal is complicated by the fact that species co-mingle on the fishing grounds. The approach of managing multiple spatially integrated fish stocks based on the weakest populations has sometimes been called'weak stock management', a term which is adopted for this analysis.

2.1. Regulatory history

An important feature of the regulatory environment for this analysis is the complicated relationship between harvest limits and estimated biomass. From 1994 to 2010, the Pacific Fisheries Management Council (PFMC) managed the fishery with species-specific output caps that took the form of 2-month limits (denominated in pounds). These limits indicated the number of pounds that each vessel could harvest of each species (or in some cases each group of species) in each 2 month period of the year. Since the limits were set in order to avoid irreparable damage to depleted populations, and since species are harvested together, fishermen could catch less than the allowable limit of some species in order to avoid exceeding the conservatively set limits on co-occurring, unhealthy species.[1]

Additionally, several regulatory interventions mark different policy regimes in the development of this fishery. These events were as follows: (i) the introduction of a limited entry licensing system in 1994, (ii) the imposition of a system of coast wide spatial closures called Rockfish Conservation Areas (RCAs) and a permit buyback, both of which went into effect between 2002 and 2003, and (iii) the imposition of individual transferable quotas (catch shares) which went into effect for the 2011 fishing season. Additionally, in 2000 the groundfish fishery was declared an economic disaster.

In 2011, the catch share system was implemented along with 100% on-board observer coverage of vessels participating in the fishery and a requirement that all overfished species be retained. This fundamentally changed the incentives facing fishermen. Prior to 2011, on-board observers recorded catch and retention of all species. In particular, if fishermen caught and discarded overfished species, this information could be used by managers to further constrain the harvest limits of target species. However, since observer coverage was not 100%, in the case that a fisherman was fishing without an observer there was no regulatory incentive to avoid overfished species since they could be discarded. In short, prior to 2011, there were no penalties for individual fishermen who caught and discarded high numbers of overfished species. This changed with the implementation of catch shares as the fishery was subject to 100% observer coverage and fishermen were required to hold quota for all overfished species that they caught (regardless of whether they landed those fish or not).

3. Methods

3.1. Productivity measurement

Total (multi) factor productivity in commercial fishing has been evaluated using a variety of nonparametric, econometric and index number approaches: [16-18] take index number approaches in their studies of commercial groundfish fisheries. A nonparametric Malmquist Index is used in [6] to assess productivity change in the Mid-Atlantic Surf Clam and Ocean Quahog Fishery.

The primary metric of productivity used here is the Lowe

[1] Here it is important to be clear about the meaning of some terms: "catch" means any fish that is encountered in a trawl. Once a fish is caught it can be discarded (thrown overboard) or it can be landed (taken to port and sold). This action has some biological significance as fishing mortality depends not only on how many fish were landed but also on how many fish were caught.

Multifactor Productivity Index[2] [19,5,20]. The Lowe Index has many desirable properties but was chosen for this study primarily because its form allows straightforward comparisons of productivity between firms and over time. As described in [5], the Lowe Multifactor Productivity Index (MFPI) is written as the ratio of a Lowe Output Quantity Index (QI) to a Lowe Input Quantity Index (XI),

$$QI_{hsit} = \frac{p_0^{`} q_{it}}{p_0^{`} q_{hs}} \; XI_{hsit} = \frac{w_0^{`} x_{it}}{w_0^{`} x_{hs}} \; MFPI_{hsit} = \frac{QI_{hsit}}{XI_{hsit}} \tag{1}$$

In Eq. (1), p_0 refers to reference prices, q_{it} are outputs of firm i in time t,x_{it} are inputs of firm i in time t, and w_0 are the reference input prices. Subscripts h, s indicate that aggregate outputs and inputs of firm i in time t are being evaluated relative to those of firm h in period s. Although there are many acceptable choices for the reference price vectors p_0 and w_0, [5,6] recommend using average prices faced by all firms over some time period of the data set. This analysis uses the coast wide average price of each harvested species, where the average is taken over the span of the data (1994–2013). Input prices (w_0) are the prices for labor, capital, and fuel averaged over the period 1994–2013. Additionally, this study uses a single reference vessel to calculate vessel level productivity. The reference vessel was chosen as the vessel with the highest gross revenue in the fleet that was also active in every year from 1994 to 2013.

3.1.1. Productivity growth

Average annual productivity growth is used to evaluate productivity change over various time periods s and $t(s + \Delta)$. This analysis applies the annualized productivity growth measurement from [5] as follows,

$$\Delta \ln MFPI_{t,s} = \frac{\ln\left(\frac{MFPI_t}{MFPI_s}\right)}{t - s} \tag{2}$$

3.1.2. Technical change

Following [5], the rate of technical change is measured using maximum possible multifactor productivity, denoted $MFPI^*$. Spatial variation in technical change is allowed by measuring $MFPI^*$ separately for each region. Additionally, technical regress is allowed. Multifactor productivity efficiency ($MFPE$) can be estimated for vessel i in region r and time t by evaluating $MFPI_{irt}/MFPI^*_{rt}$.

3.2. Measures of environmental change

Previous work has stressed the importance of considering biological changes in the fishery when evaluating the productivity of fishing vessels [16,6,20]. This study is unique in its use of both biological and regulatory changes to describe the environmental conditions faced by vessels.

3.2.1. Biomass

Similar to previous work [20], a Lowe Biomass Index is constructed in order to describe biological changes over time in the fishery. The Lowe Biomass Index calculates current period biomass relative to reference period biomass according to,

$$B_t^v = \frac{\sum_i s_{\bar{t}}^i sbb_t^i}{\sum_i s_{\bar{t}}^i sbb_{\bar{t}}^i} \tag{3}$$

In Eq. (3), $s_{\bar{t}}^i$ denotes the revenue share of species i in a reference time period and $sbb_{\bar{t}}^i$ references the biomass of species i in the reference time period. Biomass of species i in time t is sbb_t^i.

This index value uses vessel specific species revenue share averaged over the period 1994–2013 in order to weight biomass changes. Additionally, this index value uses biomass estimates normalized by estimates of unfished biomass. The use of normalized biomass allows more variation in index values. In preliminary work, the Lowe Biomass Index in Eq. (3) was calculated with estimated biomass rather than estimated biomass normalized by estimated unfished biomass. This value was dominated by biomass changes of the two most abundant species (Dover sole and sablefish) to the extent that total peak-to-trough variation in the index was less than 3% over the entire time series. The index B_t^v combines sensitivity to biomass changes for less abundant species with sensitivity to heterogeneous targeting behavior. Multifactor productivity adjusted by the vessel level biomass index is denoted $MFPI^{bv}$ and is calculated as $MFPI^{bv} = MFPI \times B^{v-1}$.

It is important to note that some species in this fishery are managed as part of a species group. For instance, greenspotted rockfish belong to the shelf rockfish group (see Table A1). For species such as these, the biomass index uses the revenue share for the entire group and the aggregate biomass of all individual species within the group. The “Biomass” column of Tables A1–A3 indicates whether the biomass time series for an individual species was included in the Lowe Biomass Index. The “Group” column of Tables A1–A3 indicates the species group that an individual species belongs to (for species that are not part of a group the “Group” value is the same as the market category).

3.2.2. Fishing opportunity

In order to compactly represent changes in harvesting opportunities set by regulators, a Lowe Fishing Opportunity Index is constructed.

$$F_t = \frac{\sum_i s_{r\bar{t}}^i y\left(g^*\right)_{rt}^i}{\sum_i s_{r\bar{t}}^i y\left(g^*\right)_{r\bar{t}}^i} \tag{4}$$

In Eq. (4), $s_{r\bar{t}}^i$ denotes the revenue share of species or species group i in region r in base time period $\bar{t}$ and $y\left(g^*\right)_{rt}^i$ references the annual allowable harvest of species i in region r in time period t assuming maximizing behavior. Since species harvest limits vary by region and by gear type, this amounts to solving for the gear choice in two month increments that maximizes total vessel harvest in the time step. The allowable harvest of species i in the reference period for each region is denoted $y\left(g^*\right)_{r\bar{t}}^i$. In order to calculate the fishing opportunity index after 2010 the total quota pounds available for each species was normalized by the number of active vessels to get “pounds of fish per vessel.” The Lowe Multifactor Productivity Index adjusted by fishing opportunities is calculated as $MFPI^f = MFPI \times F^{-1}$.

The species included in the Lowe Fishing Opportunity Index differ slightly from those included in the Lowe Biomass Index as many of the harvest limits are set on species groups rather than individual species. The Lowe Fishing Opportunity Index includes the following species with individual harvest limits: arrowtooth flounder, bocaccio rockfish, chilipepper rockfish, canary rockfish, cowcod rockfish, Dover sole, lingcod, petrale sole, sablefish, widow rockfish, yelloweye rockfish, and yellowtail rockfish. Limits set on

[2] The term “multifactor” productivity is used to make clear that, due to data limitations, it is not possible to include all relevant productive inputs in this study. Specifically, data were not available on various materials costs or taxes incurred by vessels on fishing trips. Such items could represent significant contributions to vessel level variable cost.

Table 1
Variable descriptions

Variable	Unit of measurement
DTS REV	Revenue of Dover sole, sablefish and thornyheads as a share of total vessel groundfish trawl revenue
NSM TARGET	Value equals 1 if vessel was targeting nearshore mix species assemblage and 0 otherwise
RCK TARGET	Value equals 1 if vessel was targeting rockfish species assemblage and 0 otherwise
DTS TARGET	Value equals 1 if vessel was targeting DTS species assemblage and 0 otherwise
GF REV	Groundfish trawl revenue as a share of total commercial fishing revenue
LENGTH	Length of vessel in feet
EUREKA	Value equals 1 if vessel belongs to the Eureka fleet
MONTEREY	Value equals 1 if vessel belongs to the Monterey fleet
Dbb	Buyback dummy variable: value equals 1 in years >2003
Dcs	Catch shares dummy variable: value equals 1 in years >2010

species groups include other flatfish, shelf rockfish, and slope rockfish. Although limits are set individually for longspine and shortspine thornyheads, this analysis uses combined thornyheads due to complications calculating individual revenue shares for these species.

The conceptual argument for investigating the impact of harvest limits as well as biomass is the following. If the harvest limit is not binding, then the output observed for that trip is catch. Higher catch per unit of input will generally increase productivity and greater biomass is generally thought to increase catch per unit of input. However, if the harvest limit is binding then output observed for that trip is not catch but rather the portion of catch that is retained (landings). In this case, the effect on productivity of a hypothetical increase in catch per unit of input resulting from a biomass increase also depends on how much of that catch can be retained.

3.3. Regression analysis and statistical testing

This analysis utilizes OLS and panel data fixed-effects regression, to evaluate the impact of behavioral covariates on vessel level productivity over time. Table 1 describes the variables used in regressions to summarize firm characteristics. The work of [21,22] has emphasized caution when regressing productivity estimates on contextual variables. These cautions are addressed in Section 5.

To test for differences in productivity or other characteristics between vessels belonging to different groups, *t*-tests of means are conducted. Unless otherwise stated, correlation coefficients (denoted ρ) are Pearson's product moment correlation coefficients.

3.4. Metrics

This paper examines how productivity change over time differed for groundfish trawlers with different attributes. The remainder of this section details the metrics used to define firm variability.

3.4.1. Geographic variability

Geographic variability is measured for each vessel and year by calculating the percent of time spent in each of 5 regions. Vessels were assigned to regions based on the port to which they returned most often in a particular year. In the small number of cases (55 vessel/year combinations out of a total 3046 vessel/year combinations in the data) where a vessel had a 50% split between regions, total landings were used as the tie-breaker.

Regions of the fishery are defined according to the International North Pacific Fisheries Commission boundaries (Fig. 1). These regions were chosen as the spatial unit of aggregation in order to retain as much spatial heterogeneity as possible without violating confidentiality. Additionally, in order to satisfy confidentiality requirements, the discussion is limited to vessels fishing in one of the three most populated regions: Monterey, Eureka, and Columbia.

3.4.2. Behavioral variability

Behavioral variability is defined along two lines: groundfish avidity and targeting behavior within the groundfish fishery. Groundfish avidity is measured as groundfish trawl revenues as a share of total vessel West Coast commercial fishing revenue. The intuition behind including this variable as a driver of productivity is that it may be an indicator for knowledge spillover or technology transfer. This is the idea that vessels that participate in multiple fisheries are more profit driven firms, and by virtue of 'fishing for dollars' rather than fishing for groundfish, will be more productive in all fisheries in which they participate. This segmentation applies directly to the management goal of encouraging a diversified fleet. Additionally, the familiar Herschman–Herfindahl indicator of income concentration was calculated for groundfish trawlers but this measure did not provide additional insight over the simple measures proposed here.

Targeting behavior is defined relative to three frequently pursued species assemblages within the fishery: (i) the nearshore mix assemblage (NSM) consisting of petrale sole and various other flatfish, (ii) the DTS assemblage consisting of Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish, and (iii) the rockfish assemblage consisting of all species in Table A1. These designations agree with prior biological research on fishing tactics (see [23]) and have some management relevance since the DTS assemblage is generally pursued seaward of the RCA boundaries while the nearshore mix complex is generally encountered shoreward of the RCA boundaries. Since sablefish and petrale sole are the two highest value groundfish caught in any significant quantities by trawlers, DTS and NSM strategies are sometimes referred to as sablefish and petrale targeting. As trawl gear is necessarily unselective, this analysis prefers to define targeting by assemblage rather than species.

In order to compare productivity change among vessels employing different strategies, each vessel/year combination was assigned to a single strategy in the following way. Vessel i in year t was assigned strategy s if $\frac{\sum_{k \in s} L_{ikt}}{\sum_{k \in Y} L_{ikt}} > \frac{\sum_{k \in g} L_{ikt}}{\sum_{k \in Y} L_{ikt}} \; \forall \, g \neq s$, where L_k is landings of species included in assemblage s, g denotes species assemblages (NSM, DTS, Rockfish), and Y represents all species included in the analysis. Segmenting the fleet based on species revenue and landings shares allows examination of differences in productivity that may arise because of targeting strategy.

4. Data

Data for this study come from the Pacific Fisheries Information Network (PacFIN), maintained by the Pacific States Marine Fisheries Commission. Input quantities for labor (number of crew days per year) and energy (estimated annual fuel use) come from logbooks maintained by vessel captains. Capital input use (vessel length in feet) is derived from Coast Guard records. Output prices come from fish ticket line data.

Input prices come from a variety of public sources. The price of crew labor was calculated as the opportunity cost to crew, defined as the average daily construction wage. Wages in construction employment for California, Oregon and Washington were taken from the Federal Reserve Economic Database (FRED). The price of capital is derived using the user cost of capital from [24]. Using values from [20], the resale value of a foot of vessel length is approximated as $1571. A 6% depreciation rate is applied. The user cost of capital makes use of the annual rate of return on BAA bonds. This quantity was also taken from the St. Louis Federal Reserve Bank's FRED database. Fuel costs combine estimates of total annual fuel use, measured in gallons and the average price for #2 diesel reported by the Energy Information Administration. Fuel use was estimated from a sample of vessels reporting fuel use on commercial groundfish trawl fishing trips. These estimates are available from the authors on request. Additionally, the national fuel price used in the study was compared to port level fuel prices for West Coast groundfish ports available for selected years from the Pacific States Marine Fisheries Commission. Port level fuel prices tracked the national average well over the available years (results available from the authors). All prices in the study have been converted to real 2010 dollars using the implicit GDP price deflator taken from the St. Louis Federal Reserve Bank's FRED database.

4.1. Biologic and regulatory data

Estimated biomass comes from stock assessments available on the PFMC website. To provide comparability with previous productivity estimates the same species biomass series utilized in [20] were used to construct the biomass index. Biomass data used in this study can be found in [20] or by request from the authors. Species and group-specific harvest limits used to construct the Lowe Fishing Opportunity Index were recovered from PFMC documents (Table B1).

4.2. Fleet definition

The West Coast groundfish trawl fishery is diverse and several different agencies and research groups have an interest in this fishery. In the interest of transparency, the following offers some information on the vessels included in this analysis. This study uses groundfish trawl logbooks to define limited entry groundfish trawl landings. All observations in the logbooks that occurred during a time when the vessel held a valid limited entry groundfish trawl permit were included in the analysis. Additionally, all tows targeting Pacific whiting were omitted from this study. Any tows where pounds of Pacific whiting made up over 50% of the total pounds of the tow were discarded. Finally, only vessels with at least $5000 in annual gross groundfish trawl revenues were included in the study.[3]

Finally, it important to acknowledge a key difference between this study and previous productivity estimates for the West Coast groundfish fishery. This study relies on logbook data and publicly available input price series, rather than snapshot data collected from interviews with vessel captains, because logbooks provide a longer time series. This is important because the goal of the study is to evaluate productivity change over multiple management regimes. Logbook data have been criticized because of the self-reported nature. However, there is evidence that the logbooks used in this study are accurate and void of systematic misreporting [25]. Additionally, while [20] assessed productivity change for the entire groundfish fleet, the focus of this study is on making productivity comparisons across vessels and regions over time.

[3] Anecdotal accounts have suggested that one effect of the catch share program was to encourage fishermen to switch to hook and line gear for landing sablefish, since line caught sablefish generally fetches a higher ex-vessel price. Potential productivity implications of the "gear switching" phenomenon are not considered in this analysis.

Table 2
Geometric mean of multifactor productivity estimates.

	Columbia			*Eureka*			*Monterey*		
	MFPI	*MFPI**	MFPE	MFPI	*MFPI**	MFPE	MFPI	*MFPI**	MFPE
1994	0.50	1.24	0.40	0.74	1.88	0.39	0.56	1.27	0.44
1995	0.61	1.42	0.43	0.64	1.53	0.42	0.57	1.11	0.51
1996	0.65	1.39	0.47	0.63	1.44	0.44	0.61	1.03	0.59
1997	0.58	1.47	0.39	0.54	1.08	0.49	0.54	1.16	0.47
1998	0.55	1.29	0.42	0.51	1.12	0.45	0.55	1.30	0.42
1999	0.57	1.15	0.50	0.53	1.10	0.49	0.57	1.16	0.49
2000	0.58	1.33	0.44	0.54	1.13	0.47	0.43	0.89	0.48
2001	0.51	0.92	0.56	0.48	0.82	0.58	0.46	0.89	0.52
2002	0.53	1.00	0.53	0.46	0.80	0.57	0.52	0.82	0.63
2003	0.62	1.15	0.54	0.62	1.18	0.53	0.58	0.99	0.58
2004	0.83	1.89	0.44	0.85	1.34	0.63	0.68	1.33	0.51
2005	0.85	2.14	0.40	1.14	1.63	0.70	0.78	1.45	0.54
2006	0.86	2.28	0.38	1.13	1.68	0.67	0.76	1.46	0.52
2007	0.87	1.89	0.46	1.09	1.61	0.68	0.74	1.36	0.55
2008	0.90	1.83	0.49	1.10	1.48	0.74	0.72	1.39	0.52
2009	0.80	1.56	0.51	0.96	1.45	0.66	0.67	1.29	0.51
2010	0.80	1.40	0.57	0.97	1.49	0.65	0.77	1.45	0.53
2011	1.12	1.83	0.61	1.35	2.02	0.67	0.74	1.81	0.41
2012	1.11	2.19	0.51	1.33	1.91	0.70	0.82	1.75	0.47
2013	1.20	2.07	0.58	1.24	1.83	0.68	0.91	1.82	0.50

5. Results and discussion

5.1. Productivity trends

Table 2 shows the geometric mean of the MFPI, maximum possible MFPI, and MFPE by region and year. From 1994 to just before the buyback in 2002, productivity growth was negative in Eureka and Monterey and less than 1% per year on average in Columbia. Comparison of productivity across regions during this period yields no clear indication of a most or least productive region. Mean productivity in Monterey ranged from 10% more productive to 35% less productive than the other two regions. Mean productivity in Columbia ranged from 10% more productive than Eureka to 30% less productive.

In the post-buyback period, from 2003 to 2010, consistently higher mean productivity can be observed among Columbia and Eureka vessels relative to Monterey vessels. Mean productivity in Columbia relative to Monterey was 5–25% higher from 2003 to 2010, while Eureka vessels were consistently 10–20% more productive than Monterey vessels.

Analysis of vessels accepting the buyout in 2003 did not indicate significantly lower productivity relative to vessels that did not accept the buyout. However, it is clear that the buyback fostered productivity growth among vessels that remained in the fishery. Growth rates were calculated for vessels active in the period 1999–2002 and also active following the buyback from 2003 to 2005. Average annual productivity growth for these vessels increased from −1.4% (Monterey), −1.6% (Eureka) and 2.1% per year (Columbia) in the period 1999–2002 to 26%, 45%, and 36% per year in the period 2003–2005 for the same three regions.

The implementation of catch shares appears to have further exacerbated productivity differences between regions. Taking the average of the ratios of mean productivity in Columbia to mean productivity in Monterey from 2003 to 2010 indicates productivity was 15% higher in Columbia rleative to Monterey in this period. This same ratio averaged over the years 2011–2013 showed productivity was 40% higher in Columbia than Monterey. Comparing productivity in Monterey to productivity in Eureka also using the average of ratios of mean productivity indicates Eureka was, on average, 37% more productivity than Monterey from 2003 to 2010 and 60% more productive than Monterey from 2011 to 2013. This result is worthy of some extended discussion as it relates directly

Table 3
Geometric mean productivity by region and target strategy. The percent of vessels in each regional fleet pursuing each strategy is included in parentheses.

	Columbia			Eureka			Monterey		
	DTS	NSM	RCK	DTS	NSM	RCK	DTS	NSM	RCK
1994	0.45 (35)	0.37 (12)	0.57 (53)	0.75 (82)	0.41 (8)	1.07 (10)	0.66 (65)	0.34 (23)	0.66 (12)
1995	0.63 (36)	0.46 (14)	0.65 (50)	0.63 (85)	0.49 (4)	1.15 (4)	0.61 (59)	0.35 (17)	0.68 (24)
1996	0.59 (51)	0.46 (3)	0.73 (46)	0.63 (80)	0.52 (13)	1.02 (7)	0.60 (63)	0.55 (15)	0.67 (22)
1997	0.55 (51)	0.37 (13)	0.72 (36)	0.53 (85)	0.52 (9)	0.72 (6)	0.48 (47)	0.52 (18)	0.65 (34)
1998	0.50 (45)	0.51 (8)	0.60 (47)	0.52 (83)	0.31 (6)	0.58 (11)	0.46 (40)	0.53 (10)	0.64 (50)
1999	0.55 (70)	0.35 (5)	0.70 (25)	0.53 (88)	0.44 (8)	0.75 (4)	0.57 (63)	0.52 (28)	0.67 (9)
2000	0.58 (66)	0.43 (11)	0.68 (23)	0.55 (88)	0.38 (7)	0.56 (5)	0.50 (75)	0.23 (22)	0.90 (3)
2001	0.51 (89)	0.48 (7)	0.71 (4)	0.50 (78)	0.42 (20)	0.36 (2)	0.46 (80)	0.47 (20)	
2002	0.53 (85)	0.52 (14)	0.80 (1)	0.47 (78)	0.42 (21)		0.51 (79)	0.54 (21)	
2003	0.64 (90)	0.49 (10)		0.66 (84)	0.46 (16)		0.62 (79)	0.44 (21)	
2004	0.88 (86)	0.60 (14)		1.01 (87)	0.25 (13)		0.86 (69)	0.46 (26)	0.27 (5)
2005	0.87 (89)	0.66 (11)		1.16 (94)	0.84 (6)		0.85 (67)	0.65 (33)	
2006	0.91 (82)	0.66 (18)		1.21 (76)	0.92 (24)		0.89 (69)	0.55 (31)	
2007	0.93 (91)	0.50 (9)		1.09 (100)			0.87 (65)	0.55 (35)	
2008	0.94 (94)	0.43 (6)		1.10 (100)			0.81 (80)	0.47 (13)	0.40 (7)
2009	0.84 (91)	0.49 (9)		0.96 (100)			0.79 (77)	0.36 (15)	0.41 (8)
2010	0.88 (89)	0.37 (11)		0.97 (100)			0.87 (71)	0.59 (71)	0.50 (7)
2011	1.26 (88)	0.49 (12)		1.35 (100)			0.92 (73)	0.41 (18)	0.46 (9)
2012	1.16 (87)	0.68 (11)	2.19 (2)	1.31 (93)	1.60 (7)		1.02 (70)	0.59 (10)	0.44 (20)
2013	1.24 (78)	0.97 (17)	1.40 (5)	1.21 (92)	1.60 (8)		0.96 (84)	0.59 (8)	0.84 (8)

to management concerns regarding whether regulatory intervention will alter the geographic distribution of fishing activity, possibly with severe economic consequences for some fishing communities.

While the impacts of catch shares on productivity appeared notably larger for the Columbia and Eureka fleets, this study finds no compelling evidence that quota trading shifted the geographic distribution of landings away from the Monterey region. Regional landings of Dover sole, petrale sole, and sablefish, expressed as the share of total coast wide trawl caught pounds of each species, were regressed against a time trend where the effect of catch shares was captured by the interaction of the time trend with a dummy variable indicating years before and after catch shares (results available from the authors). If catch shares caused a region to gain or lose share of any of these species then the expected coefficient on the interaction variable would be significant. Results for the Monterey region do not support the hypothesis of an inter-regional shift in landings shares. This is particularly important because, although quota for many species was designated by area and could not be traded north and south of 40°10′, quota for the main targeted species in this analysis (Dover sole, sablefish and petrale sole) were not geographically defined.[4]

Results do indicate there was greater fleet consolidation in Columbia and Eureka relative to Monterey following catch share implementation; fleet size in Monterey, Eureka, and Columbia from 2011 to 2013 was 79%, 68% and 58% of the of each region's active 2008–2010 fleet.

Here, it is important to acknowledge two features that restricted quota trades during the study period: (i) for the first two years of the program only quota pounds could be traded, quota share could not, and (ii) catch share regulations limit the amount of quota that can be allocated to each vessel. While these restrictions may have effected whether particular vessels could obtain more quota pounds than their initial allocation, it is not immediately clear how they would directly constrain the spatial extent of trading. Nevertheless, it is important to understand that quota trading patterns may have changed after 2012 when vessels could trade share in addition to leasing pounds.

In all regions it was the case that vessels which were idled following catch share implementation tended to be less productive. A *t*-test was used to compare mean productivity values for vessels active from 2008 to 2010 but idled from 2011 to 2013 and vessels active in both periods. In all regions, vessels active in the catch share period were significantly ($p < 0.1$) more productive in the pre-catch share period from 2008 to 2010 than vessels that were idled following catch shares. Differences in mean productivity between catch share active and catch share idled vessels within regions were significant ($p < 0.1$) and values ranged from 24% more productive (Columbia) to 38% more productive (Monterey). This result is important in explaining the post-catch share productivity difference between Monterey and the other regions. Within regions, following catch shares, fishing activity clearly flowed toward more productive vessels. This effect was relatively more pronounced in the Columbia and Eureka regions where fleet consolidation was greater.

Vessels active from 2011 to 2013 also experienced a notable increase in the rate of productivity growth following catch shares. From 2008 to 2010, for vessels active both before (2008–2010) and after (2011–2013) catch share implementation, growth in mean productivity was −2.7% per year in Monterey, −3.5% per year in Eureka and −5% in Columbia. From 2011 to 2013 , growth in mean productivity for these vessels was 2.7% per year in Monterey, 5.8% per year in Eureka, and 10% per year in Columbia.

In addition to regional affiliation, vessels distinguish themselves from one another by the output mix they pursue within this multispecies fishery. Table 3 shows that vessels targeting DTS species were generally more productive in the post-buyback fishery than other vessels. This is particularly evident in the post-catch share fishery where vessels targeting DTS in Columbia were between 30% and 150% more productive than vessels targeting NSM. Vessels targeting DTS in Monterey were 60–124% more productive than vessels targeting NSM during this time. In Eureka, the small number of vessels targeting NSM were about 30% more productive than those targeting DTS.

Although they are not exhaustively examined here there are two possible environmental explanations for the increasing productivity advantage of DTS targeting. First, retention limits on

[4] Sablefish has separate quota pounds north and south of 36° N latitude but since this study includes only vessels fishing north of 36° N latitude, this designation is not a limiting feature of the analysis.

rockfish species became increasingly restrictive during the period 1994–2002. This may have led to increased costs in the form of crew labor necessary for on-board sorting and discarding or search costs necessary to avoid high rockfish bycatch areas. These limits may have disproportionately impacted nearshore mix fishermen as DTS species are generally pursued farther offshore from rockfish habitat. Also, following the buyback of 2003 and establishment of the Rockfish Conservation Areas, gear restrictions were introduced for vessels fishing shoreward of the RCA boundary. These restrictions would not have impacted vessels focusing on DTS as those species are generally targeted seaward of the RCA boundary. Additionally, the estimated biomass for DTS species is larger than for other species (sablefish and Dover sole account for almost half of the total estimated biomass of groundfish species) and the percent of the fleet targeting DTS has been steadily increasing since 1994.

Regional differences in targeting strategies, and the resulting output mix, provide a possible explanation for the productivity gap between Monterey and the other regions during the post-buyback period from 2003 to 2010. While the proportion of total active vessels in each region pursuing the DTS strategy has been increasing across all regions since 1994, non-DTS vessels made up a larger share of the Monterey fleet then non-DTS vessels in the other regions. Since Monterey and Columbia vessels that engaged in the same fishing strategies did not exhibit notable differences in average productivity during this time, the difference in mean productivity between Monterey and other regions can possibly be explained by the fact that Monterey had more vessels engaged in low productivity fishing strategies.

Finally, the remainder of this section examines the influence of environmental factors on productivity. Differences in productivity dynamics across regions are not well explained by changes in environmental conditions, as measured by the vessel level Lowe Biomass Index. Table 4 shows biomass-adjusted productivity estimates and biomass-adjusted estimates of $MFPI^{*}$ across regions. From the table one can see that the widening gap between mean productivity in Monterey and mean productivity in the other regions persists even after adjusting for biomass changes. Here, one important feature of the Lowe Biomass Index should be addressed: although the index accounts for regional heterogeneity in output mix by applying revenue share weights at the vessel level, changes in species-specific resource abundance are measured coast wide. There is some evidence [13] that species densities vary along the West Coast. If density, and by extension, catchability varies over space then it may be important to explore possible local measures of biomass change for use in productivity assessments. However, if differences in catchability across space were impacting regional productivity scores one might expect to see this reflected in large gaps in $MFPI^{*}$. While Table 2 does indicate lower $MFPI^{*}$ in the Monterey region from 2005 to 2010, the $MFPI^{*}$ difference between Monterey and the other regions appears to be declining from 2011 to 2013.

Table 4
Geometric mean of biomass-adjusted productivity and maximum possible productivity

	Columbia			Eureka			Monterey		
	$MFPI^{bv}$	$MFPI^{*bv}$	$MFPI^{f}$	$MFPI^{bv}$	$MFPI^{*bv}$	$MFPI^{f}$	$MFPI^{bv}$	$MFPI^{*bv}$	$MFPI^{f}$
1994	0.51	1.29	0.24	0.74	2.00	0.53	0.63	1.53	0.30
1995	0.63	1.50	0.35	0.65	1.59	0.62	0.63	1.20	0.28
1996	0.68	1.61	0.38	0.66	1.60	0.64	0.68	1.20	0.31
1997	0.62	1.55	0.37	0.56	1.16	0.68	0.62	1.31	0.30
1998	0.58	1.34	0.39	0.54	1.21	0.85	0.61	1.40	0.38
1999	0.60	1.22	0.39	0.55	1.18	0.79	0.64	1.25	0.49
2000	0.61	1.38	0.48	0.56	1.20	0.82	0.48	0.96	0.41
2001	0.53	0.95	0.45	0.49	0.86	0.82	0.50	0.91	0.42
2002	0.54	1.08	0.69	0.46	0.83	1.10	0.53	0.82	0.73
2003	0.62	1.18	0.90	0.61	1.21	1.43	0.57	0.99	1.01
2004	0.78	1.71	0.98	0.79	1.32	1.28	0.65	1.30	0.77
2005	0.78	2.00	0.84	1.07	1.58	1.59	0.72	1.37	0.83
2006	0.79	2.22	1.45	1.06	1.57	2.10	0.70	1.38	1.16
2007	0.81	1.77	1.47	1.03	1.51	2.03	0.68	1.28	1.15
2008	0.84	1.77	1.04	1.04	1.43	1.33	0.67	1.34	0.82
2009	0.76	1.53	0.79	0.92	1.39	0.96	0.62	1.25	0.66
2010	0.80	1.40	0.79	0.97	1.49	0.97	0.77	1.45	0.77
2011	1.15	1.87	1.28	1.37	2.05	1.49	0.76	1.84	0.80
2012	1.15	2.25	1.27	1.37	1.95	1.41	0.85	1.79	0.86
2013	1.25	2.15	1.50	1.28	1.88	1.41	0.94	1.86	1.05

The fishing opportunity index is explored in this analysis because, contrary to expectations, fishing opportunities are not strongly related to biomass changes in this fishery. Let (ρ, p) denote the correlation between fishing opportunity and biomass and associated p-value: these values equal $(-0.52, 0.018)$ for Monterey, $(-0.33, 0.15)$ for Eureka, and $(-0.63, 0.003)$ for Columbia. Since fisheries managers are required to meet rebuilding targets for overfished species, increases in biomass may not necessarily lead to increased harvest limits.

The fishing opportunity index was found to be inversely correlated with productivity: (ρ, p) equal to $(-0.40, 0.08)$ for Monterey, $(0.25, 0.29)$ for Eureka, and $(-0.59, 0.007)$ for Columbia. A potential pathway for fishing opportunities to influence productivity is through its effect on fleet restructuring. As groundfish fishing opportunities decline, some vessels, possibly including those that lack the technology to diversify into other fisheries, will exit the fleet. Alternatively, some vessels will allocate larger shares of effort to other fisheries in an attempt to maintain total vessel revenues. The marginal effect of a unit increase in groundfish dependence on productivity is negative as, all else equal, allocating inputs away from groundfish and towards other fisheries will tend to raise the ratio of groundfish outputs to inputs. Declining fishing opportunities may lead to observed increases in productivity in this study as more groundfish dependent vessels drop out and remaining vessels diversify into other fisheries. Results of this analysis indicate that more groundfish dependent vessels tended to exit through the buyback. A t-test of means between groundfish dependence from 1994 to 2002 for vessels selling in the buyback and those not selling indicated significantly ($p < 0.01$ in all regions) higher groundfish dependence among sellers.

Results also indicate that, among buyback non-sellers, there was significant ($p < 0.05$) positive correlation between the fishing opportunity index and groundfish dependence for Monterey $(\rho = 0.1)$ and Columbia $(\rho = 0.21)$ vessels. Despite the implied differences in regional effort responses to changing fishing opportunities, Table 4 shows that fishing opportunities do not appear to offer a compelling explanation for Monterey's relatively low productivity in the post-buyback fishery.

5.2. Productivity drivers

The final step in this analysis attempts to isolate the impacts of strategy choice and regional location on vessel productivity. The approach taken here is to use regression analysis to estimate the marginal effect of these two characteristics. Concerning strategy choice, this discussion focuses on the DTS and NSM strategies since the rockfish strategy was not employed by Columbia and Eureka vessels over large portions of the post-buyback time period.

5.2.1. Model selection

A concern with regressions using productivity as the dependent variable [21] is whether or not the proposed explanatory variables are independent of the factors of production. Independence was tested by regressing DTS revenue shares, groundfish revenue shares, and regional indicator variables on crew days.[5] DTS revenue share was not found to be independent of the factors of production (model selection results are included in Appendix C). A likely explanation for this dependence is that the fishery is output constrained. Under the trip limit system, as the output constraint on a target species becomes binding the vessel either exits the groundfish fishery (tending to reduce days-at-sea relative to other vessels) or targets another species (diluting the revenue share of the target species relative to total revenue). The categorical variables for strategy choice (*DTS target*, *RCK target*) were found to be independent of the factors of production. This analysis proceeds by using these strategy variables to model productivity.

Groundfish revenue share was also found to be significantly related to crew days. This may be a result of only observing a portion of the vessels' operations. Less groundfish dependent vessels will tend to fish more in other fisheries and less in the groundfish fishery and, since these data do not include inputs allocated to other fisheries, less groundfish dependent vessels have lower input usage. An important implication here is that this study can only observe that less groundfish dependent vessels were more productive within the groundfish fishery. The present study cannot address whether increases in groundfish productivity associated with allocating inputs to other fisheries was perhaps offset by declining vessel productivity in the fisheries into which effort flowed.

Structural breaks in the data were tested using interactions between policy dummy variables and strategy choice and region variables. Results indicate that impacts of strategy and regional location on productivity differed before and after the buyback and before and after catch share implementation.

5.2.2. Estimation strategy

Based on results of the model selection exercise, and to avoid conflating time effects with strategy or spatial effects, models are estimated separately for three discrete time periods: (i) 1994–2002, (ii) 2003–2010, and (iii) 2011–2013. Additionally, there are very few vessels in the study that fish in more than one region or employ more than one strategy within a time window. This makes it difficult to control for unobserved vessel effects as any observable time-invariant covariate will be unidentified. This study takes the approach of estimating models to identify the regional effect and strategy effect separately. The regional models are denoted R1–R3 in Table 5 and control for strategy choice by using a subsample of vessels employing the DTS strategy (It should be noted that regressions using only NSM targeting observations were also explored. Results were consistent with conclusions from the DTS targeting models but, with far fewer vessels employing the NSM strategy, less significant results were obtained). These models compare productivity for vessels employing the same strategy in different regions. The strategy models are labeled S1–S3 in Table 5. These models control for unobservable vessel effects by using the fixed-effects estimator. To avoid conflating the strategy effect with a regional effect, only vessels that fished exclusively in a single region in the relevant time window are included (in practice this involves omitting less than 8% of the observations in any year).

5.2.3. Estimation results

Regression models presented in Table 5 examine the marginal impacts on productivity of location and strategy choice. Three results from Table 5 stand out as worthy of exploration. First, Model R2 indicates that Eureka vessels were significantly more productive than Columbia and Monterey vessels following the buyback. Since the buyback had a bigger fleet reduction effect in Eureka than anywhere else, this result conforms to expectations. However, Model 5 does not indicate a significant marginal effect of the Eureka location variable estimated over the 2011–2013 period. This suggests that the buyback productivity effect was not persistent.

Second, prior to catch shares, strategy choice does not appear to have had a strong impact on productivity. Specifically, Models S1 and S2 show no significant effect of DTS targeting among vessels employing multiple strategies within a time window. This suggests that simply changing targeting strategies is unlikely to improve a vessel's productivity.[6] An important caveat here is that,

Table 5
Regression results. Standard errors appear in parentheses below the parameter estimates."FE" indicates the fixed-effects estimator , "OLS" indicates ordinary least squares, "nregion" indicates the number of regions fished in by a vessel in each year. NSM targeting vessels form the basis for comparison for Models S1–S3 and Columbia vessels form the base for Models R1–R3. Yearly fixed-effects are accounted for in the regressions by including dummy variables for each year. These estimates are suppressed from the table. Significance of the parameter estimates are denoted by asterisks: "*" indicates a p-value less than or equal to 0.1, "**" indicates a p-value less than or equal to 0.05, and "***" indicates a p-value less than or equal to 0.01.

Covariate	Dependent variable					
	MFP	MFP	MFP	MFP	MFP	MFP
DTS TARGET		−0.035		0.003		−0.308***
		(0.027)		(0.037)		(0.101)
RCK TARGET		0.001		−0.162		−0.096
		(0.030)		(0.109)		(0.124)
LENGTH	0.001**		0.005***		0.002	
	(0.000)		(0.000)		(0.003)	
EUREKA	0.021		0.155***		0.087	
	(0.014)		(0.025)		(0.067)	
MONTEREY	0.004		0.008		−0.184**	
	(0.017)		(0.030)		(0.083)	
Method	OLS	FE	OLS	FE	OLS	FE
Sample	1994–2002, target=DTS	1994–2002, nregion=1	2003–2010, target=DTS	2003–2010, nregion=1	2011–2013, target=DTS	2011–2013, nregion=1
Observations	964	1102	718	770	160	188
Adjusted R2	0.07	0.08	0.21	0.13	0.04	0.13
Model	R1	S1	R2	S2	R3	S3

[5] This test was also performed using the fuel input. These results are available from the authors and confirm the dependence of DTS revenue share on factors of production.

[6] To test the sensitivity of these results to the ad-hoc strategy assignment an alternative strategy assignment was explored. Rather than assign targeting strategy based on assemblage, vessels were assigned the targets "petrale sole", "rockfish", or "sablefish" according to which species or species group made up the largest share

particularly in the post-buyback fishery, only about 14% of the fleet employed multiple targeting strategies. The overwhelming majority of vessels exclusively employed the DTS strategies and these were the highest productivity vessels in the fishery.

Following catch share implementation, multi-strategy vessels were more productive when employing the NSM strategy than the DTS strategy (Model S3). This may have been driven at least in part by a large increase in the effective abundance of petrale sole. In 2011, 1.9 million pounds of petrale sole quota and 5.6 million pounds of sablefish quota were allocated to the fishery. In 2013, 5.1 million pounds of petrale sole and 4 million pounds of sablefish quota were allocated.

Finally, Table 3 shows that in the post-buyback fishery, productivity in the Monterey fleet tended to lag behind Columbia and Eureka as a greater share of the Monterey fleet was engaged in the low productivity NSM strategy. Table 5 (Model R3) shows that, even when strategy choice is held constant, Monterey vessels in the post-catch share fishery were significantly less productive than Columbia vessels. Models R1 and R2 in Table 5 do not reveal significant differences between Monterey vessels and other vessels in the periods prior to catch shares. Additionally, annual average productivity growth from 2010 to 2013 was 5.5% per year in Monterey, notably lower than growth in Columbia (13.5% per year) and Eureka (8.2% per year) over the same period. These results suggest that the implementation of the catch share program had a stronger positive impact on productivity for Columbia and Eureka vessels than for Monterey vessels, and that this difference is not well explained by differences in fishing tactics.

A final note of caution regarding the regression results: most vessels in the fishery fish in a single region and employ a single strategy exclusively. Therefore, the result that strategy choice generally does not influence productivity when other vessel characteristics are controlled for may have questionable practical significance.

6. Conclusion

Results of this analysis support the following conclusion of likely interest to policy makers on the West Coast: notable growth in multifactor productivity occurred across all regions of the groundfish fishery following: (i) a permit buyback in 2003 and (ii) the implementation of the catch share program in 2011. In both cases productivity was stagnant or declining in the years leading up to the policy intervention. One caveat to this general conclusion was uncovered that will also be of interest to fisheries managers: change in mean productivity and maximum possible multifactor productivity following catch share implementation was greater for vessels in the Columbia and Eureka regions of the fishery. Multifactor productivity efficiency was also notably lower in Monterey than in other regions from 2011 to 2013.

Results regarding the impact of fishing strategy on productivity were mixed. While the Monterey fleet clearly had a relatively large share of vessels engaged in a low productivity fishing strategy, there was little econometric evidence that vessels could improve productivity simply by changing strategies. Moreover, significant differences were found in the post-catch share fishery between Monterey vessels and vessels from other fleets even when comparisons were made across vessels employing the same strategy. One method of controlling for variation in output mixes across space was through the use of a Lowe Biomass Index to adjust productivity. This index assigned weights to species biomass changes that reflected the variation in species' contributions to vessels revenues across firms in the fishery. Productivity differences across regions were not found to be well explained by this index.

Results also indicate a regional effect of catch shares in terms of vessel participation. Vessels idled since catch share implementation were the least productive vessels in each region but not necessarily the least productive vessels coast wide. Further research is needed on the spatial extent of quota trading, particularly in the post-2012 period when quota share became tradable. However these results suggest that the catch share system did not consolidate landings among the most productive vessels coast wide but rather that consolidation of fishing activity primarily occurred among the most productive vessels in each region. This finding has important management implications as policy makers and industry participants are often concerned with whether transferable quota will reallocate landings away from some communities with potentially severe economic impacts. Our analysis does not find this to be the case at the regional level with the West Coast groundfish trawl catch share program.

Two cautions regarding this analysis are worth emphasizing. First, the data utilized here do not include observations on some potentially important variable costs such as landings taxes, monitoring costs and quota purchase. Since productivity for each vessel is estimated relative the same reference vessel, the omission of these additional costs will only bias the results if the ratio of the omitted cost to total vessel cost varies significantly across the fleet. Second, data do not include input usage across all fisheries in which vessels participate. The implication of this is that any behavioral response to groundfish catch shares that might have increased productivity when evaluated across all of a vessel's fishing operations cannot be observed.

(*footnote continued*)
of annual vessel revenue. Regression results were not affected by this alternative targeting assignment.

Acknowledgements

The authors would like to thank Ron Felthoven, John Field, Abigail Harley, Rosemary Kosaka, Chris O'Donnell, John Ruggiero, Cameron Speir, Erin Steiner, Cynthia Thomson, and John Walden for helpful comments. Trevor Collier is grateful for grant funding from the National Marine Fisheries Service. Both authors also wish to acknowledge Don Pearson for critical help with the data and Alice Thomas-Smyth for research assistantship. All errors or omissions are the fault of the authors.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2015.06.002.

References

[1] F. Eide, F. Skjold, Olsen, O. Flaaten, Harvest functions: the Norwegian bottom trawl cod fisheries, Mar. Resour. Econ. 18 (2003) 81–94.
[2] K.J. Fox, R.Q. Grafton, T. Kompas, T. Nhu Che, Capacity reduction, quota trading, and productivity: the case of a fishery, Aust. J. Agric. Resour. Econ. 50 (2006) 189–206.
[3] M.M. Oliveira, M.B. Gaspar, J.P. Paixao, S. Camanho, Productivity change of the artisanal fishing fleet in Portugal: a malmquist index analysis, Fish. Res. 95 (2009) 189–197.
[4] P.M. Clay, A. Kitts, P. Pinto da Silva, Measuring the social and economic performance of catch share programs: definition of metrics and application to the U.S. Northeast Region groundfish fishery, Mar. Policy 44 (2013) 27–36.
[5] C.J. O'Donnell, Nonparametric estimates of the components of productivity

and profitability changes in U.S agriculture, Am. J. Agric. Econ. 94 (2012) 873–890.
[6] J.B. Walden, J.E. Kirkley, R. Fare, P. Logan, Productivity change under an individual transferable quota management system, Am. J. Agric. Econ. 94 (2012) 913–928.
[7] A.G. Guttormsen, K.H. Roll, Technical efficiency in a heterogeneous fishery: the case of Norwegian groundfish fisheries, Mar. Resour. Econ. 26 (2011) 293–307.
[8] B. Mansfield, Property regime or development policy? explaining growth in the U.S. Pacific Groundfish Fishery, Prof. Geogr. 53 (2001) 384–397.
[9.] F. Conway, W. Shaw, Socioeconomic lessons learned from the response to the federally-declared West Coast groundfish disaster, Fisheries 33 (2008) 269–277.
[10] R.R. Miller, J.C. Field, J.A. Santora, I.D. Schroeder, D.D. Huff, M. Key, D.E. Pearson, A.D. MacCall., A spatially distinct history of the development of California groundfish fisheries, PloS One 9 (2014) e99758.
[11] S. Ralston, West Coast groundfish harvest policy, N. Am. J. Fish. Manag. 22 (2002) 249–250.
[12] Y.W. Lee, D.B. Sampson, Spatial and temporal stability of commercial groundfish assemblages off oregon and washington as inferred from Oregon trawl logbooks, Can. J. Fish. Aquat. Sci. 57 (2000) 2443–2454.
[13] N. Tolimieri, Patterns in species richness, species density, and evenness in groundfish assemblages on the continental slope of the U.S. Pacific coast, Environ. Biol. Fishes 78 (2007) 241–256.
[14] J. Mason, R. Kosaka, A. Mamula, C. Speir, Effort changes around a marine reserve: the case of the California Rockfish Conservation Area, Mar. Policy 36 (2012) 1054–1063.
[15] P. Watson, T. Johnson, Federal fishery policy and the geographic distribution of commercial US West Coast fish landings: insights from the 2003 federal groundfish permit buyback, Mar. Resour. Econ. 27 (2012) 289–301.
[16] D. Squires, Productivity measurement in common property resource industries: an application to the Pacific coast trawl fishery, RAND J. Econ. (1992) 221–336.
[17] E. Di Jin, H. Thunberg, Kite-Powell, K. Blake, Total factor productivity change in the New England Groundfish Fishery: 1964–1993, J. Environ. Econ. Manag. 44 (2002) 540–556.
[18] J.B. Walden, Economic health of the Northeast US multispecies trawl fleet 1996–2010, Fish. Res. 139 (2013) 98–104.
[19] W.E. Diewert, A.O. Nakamura, Essays in Index Number Theory, first ed., North Holland, Amsterdam, 1993.
[20] J. Walden, J. Agar, R. Felthoven, A. Harley, S. Kasperski, J. Lee, A. Mamula, J. Stephen, J. Strelcheck, E. Thunberg, Productivity change in U.S. catch shares fisheries Technical report, Department of Commerce, NOAA (2014).URL http://spo.nmfs.noaa.gov/tm/TM146.pdf.
[21] R.D. Banker, R. Natarajan, Evaluating contextual variable affecting productivity using data envelopment analysis, Oper. Res. 56 (2008) 48–58.
[22] L. Simar, P.W. Wilson, Two-stage dea: caveat emptor, J. Product. Anal. 36 (2011) 205–218.
[23] J.B. Rogers, E.K. Pikitch., Numerical definition of groundfish assemblages caught off the coasts of Oregon and Washington using commercial fishing strategies, Can. J. Fish. Aquat. Sci. 49 (1992) 2648–2656.
[24] B.M. Balk, Measuring and decomposing capital input cost, Rev. Income Wealth 57 (2011) 48–58.
[25] A. Thomas-Smyth, C. Speir, A. Mamula, Assessing the accuracy of high spatial resolution effort data: comparing VMS and logbook data in the California Groundfish Trawl Fishery NOAA Fisheries, Southwest Fisheries Science Center Working Paper (2014).